CEOS-ARD - Synthetic Aperture Radar - Geocoded Single-Look Complex

CEOS Analysis Ready Data (CEOS-ARD) are satellite data that have been processed to a minimum set of requirements and organized into a form that allows immediate analysis with a minimum of additional user effort and interoperability both through time and with other datasets.

Product Family Specification: Synthetic Aperture Radar, Geocoded Single-Look Complex (SAR-GSLC)

Applies to: This PFS is specifically aimed at users interested in exploring the potential of SAR but who may lack the expertise or facilities for SAR processing.

The CEOS-ARD Geocoded Single-Look Complex (GSLC) product is relevant to interferometric studies. The GSLC product is derived from the range-Doppler (i.e. slant range) Single-Look Complex (SLC) product using a DEM and the orbital state vectors and output in the map projected system. The phase of a geocoded SLC is "flattened" with respect to a reference orbit and to a DEM, to eliminate topographic phase contributions (H. Zebker 2017; Zheng and Zebker 2017). The sample spacing of the GSLC product in the map coordinate directions is comparable to the full resolution original SLC product. The GSLC product can be directly overlaid on a map or combined with other similar GSLC products to derive interferograms and create change maps, for example. Since the GSLC phase is flattened, the phase difference between two GSLC products acquired on a same relative orbit produces an interferogram referring only to surface displacement and noise (i.e., no topographic fringes). The GSLC product may optionally be radiometrically terrain corrected such that the squared amplitude yields γ_T^0.

Document History

Not available yet

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Glossary

ATBD
: Algorithm Theoretical Basis Document

Auxiliary Data
: The data required for instrument processing, which does not originate in the instrument itself or from the satellite. Some auxiliary data will be generated in the ground segment, whilst other data will be provided from external sources, e.g., DEM, aerosols.

CEOS-ARD
: Committee on Earth Observation Satellites - Analysis Ready Data

DEM
: Digital Elevation Model

DOI
: Digital Object Identifier

GSLC
: Geocoded Single-Look Complex

InSAR
: Interferometric Radar

NRB
: Normalised Radar Backscatter

ORB
: Ocean Radar Backscatter

POL
: Polarimetric Radar

RTC
: Radiometrically Terrain Corrected

SAR
: Synthetic Aperture Radar

SI
: International System of Units

SLC
: Single-Look Complex

STAC
: SpatioTemporal Asset Catalog

URL
: Uniform Resource Locator, a reference to a web resource that specifies its location on a computer network and a mechanism for retrieving it.

UTC
: Coordinated Universal Time

WGS84
: World Geodetic System 1984

Introduction

What are CEOS Analysis Ready Data (CEOS-ARD) products?

CEOS-ARD products have been processed to a minimum set of requirements and organized into a form that allows immediate analysis with a minimum of additional user effort. These products would be resampled onto a common geometric grid (for a given product) and would provide baseline data for further interoperability both through time and with other datasets.

CEOS-ARD are intended to be flexible and accessible products suitable for a wide range of users for a wide variety of applications, particularly time series analysis and multi-sensor application development. They are also intended to support rapid ingestion and exploitation via high-performance computing, cloud computing and other future data architectures. They may not be suitable for all purposes and are not intended as a *replacement* for other types of satellite products.

When can a product be called CEOS-ARD?

The CEOS-ARD branding is applied to a particular product once:

- that product has been assessed as meeting CEOS-ARD requirements by the agency or other entities responsible for production and distribution of the product, and
- that the assessment has been peer reviewed by the relevant CEOS team(s).

Agencies or other entities considering undertaking an assessment process should consult the CEOS-ARD Governance Framework or contact ard-contact@lists.ceos.org.

A product can continue to use CEOS-ARD branding as long as its generation and distribution remain consistent with the peer-reviewed assessment.

What is the difference between Threshold and Goal?

Threshold (or: minimum) requirements are the **minimum** that is needed for the data to be analysis ready. This must be practical and accepted by the data producers.

Goal (or: desired) requirements (previously referred to as “Target”) are the ideal; where we would like to be. Some providers may already meet these.

Products that meet all *threshold* requirements should be immediately useful for scientific analysis or decision-making.

Products that meet *goal* requirements will reduce the overall product uncertainties and enhance broad-scale applications. For example, the products may enhance interoperability or provide increased accuracy through additional corrections that are not reasonable at the *threshold* level.

Goal requirements anticipate continuous improvement of methods and evolution of community expectations, which are both normal and inevitable in a developing field. Over time, *goal* specifications may (and subject to due process) become accepted as *threshold* requirements.

Requirements

General Metadata

These are metadata records describing a distributed collection of pixels. The collection of pixels referred to must be contiguous in space and time. General metadata should allow the user to assess the *overall* suitability of the dataset, and must meet the requirements listed below.

Traceability (`general-metadata-traceability`)

Goal requirements:

Data must be traceable to SI reference standard.

Notes:

1. Relationship to (**measurements/uncertainty?**) or item 3.5 (SAR). Traceability requires an estimate of measurement uncertainty.
2. Information on traceability should be available in the metadata as a single DOI landing page.

Metadata Machine Readability (`general-metadata-machine-readability-sar`)

Goal requirements:

As threshold, but metadata is formatted in accordance with CEOS-ARD SAR Metadata Specifications, v.1.1, or in a community endorsed standard that facilitates machine-readability, such as ISO 19115-2, Climate and Forecast (CF) convention, the Attribute Convention for Data Discovery (ACDD), etc.

Threshold requirements:

Metadata is provided in a structure that enables a computer algorithm to be used consistently and to automatically identify and extract each component part for further use.

License / Copyright (`general-metadata-license`)

Threshold requirements:

The license terms are provided. If required by the data provider, copyright is indicated in the metadata.

Source Metadata

These are metadata records describing (detailing) **each** acquisition (source data) used to generate the ARD product. This may be one or mutliple acquisitions, depending on the ARD product.

Sequential ID (`source-metadata-sequential-id`)

Threshold requirements:

Each acquisition is identified through a sequential identifier in the metadata, e.g. 1, 2, 3.

Data Collection Time (`source-metadata-time-sar`)

Threshold requirements:

Number of source data acquisitions of the data collection is identified. The start and stop UTC time of data collection is identified in the metadata, expressed in date/time. In case of composite products, the dates/times of the first and last data takes and the per-pixel metadata Section "per-pixel-per-pixel-metadata-acquisition-id" is provided with the product.

Product Metadata

Information related to the CEOS-ARD product generation procedure and geographic parameters.

Product Type (`product-metadata-product-type`)

Threshold requirements:

- CEOS-ARD product type name
- Reference to CEOS-ARD PFS document as URL

Notes:

1. In case of compliance with more than one product type, multiple product type names and URLs must be provided.

Bounding Box (`product-metadata-bounding-box`)

Threshold requirements:

Two opposite corners of the measurement file (bounding box, including any zero-fill values) are identified, expressed in the coordinate reference system defined in Section "product-metadata-crs".

Notes:

1. Four corners of the measurement file are recommended for scenes crossing the Antemeridian, or the North or the South Pole.

Coordinate Reference System (`product-metadata-crs`)

todo

Goal requirements:

todo

Threshold requirements:

todo

Geometric Correction Algorithm (`product-metadata-geometric-correction-algorithm`)

Goal requirements:

Metadata references, e.g.: - A metadata citable peer-reviewed algorithm, - Technical documentation regarding the implementation of that algorithm expressed as URLs or DOIs - The sources of auxiliary data used to make corrections such as elevation model(s) and reference chip-sets. - Resampling method used for geometric processing of the source data.

Notes:

1. Examples of technical documentation can include e.g., an Algorithm Theoretical Basis Document (ATBD) or a product user guide.

Per-Pixel Metadata

The following minimum metadata specifications apply to each pixel. Whether the metadata are provided in a single record relevant to all pixels or separately for each pixel is at the discretion of the data provider. Per-pixel metadata should allow users to discriminate between (choose) observations on the basis of their individual suitability for applications.

Cloud Optimized Formats (`per-pixel-cloud-optimized-formats`)

Goal requirements:

All files are provided using cloud-optimized file formats.

Acquisition ID Image (`per-pixel-per-pixel-metadata-acquisition-id`)

Goal requirements:

In case of image composites, the sources for each pixel are uniquely identified.

Threshold requirements:

Required for multi-source product only.

Acquisition ID, or acquisition date, for each pixel is identified.

In case of multi-temporal image stacks, use source acquisition ID (i.e., Section “source-metadata-sequential-id”) to list contributing images.

In case of date, data represent (integer or fractional) day offset to reference observation date (in UTC). Date used as reference (“Day 0”) is provided in the metadata.

Pixels not representing a unique date (e.g., pixels averaged in image overlap zones) are flagged with a pre-set pixel value that is provided in the metadata.

File format specifications/contents provided in metadata:

- Sample type (Day, Time, ID)
- Data Format (GeoTIFF, HDF5, NetCDF, …)
- Data Type (Int, Float, …)
- Bits per sample
- Byte Order

Radiometrically Corrected Measurements

The requirements indicate the necessary outcomes and, to some degree, the minimum steps necessary to be deemed to have achieved those outcomes. Radiometric corrections must lead to normalised measurement(s) of backscatter intensity and/or decomposed polarimetric parameters. As for the per-pixel metadata, information regarding data format specification needs to be provided for each record. The requirements below must be met for all pixels/samples/observations in a collection.

Cloud Optimized Formats (`measurements-cloud-optimized-formats`)

Goal requirements:

All files are provided using cloud-optimized file formats.

Backscatter Measurements (GSLC) (`measurements-measurements-backscatter-gslc`)

Threshold requirements:

Radiometric and Phase Terrain-flattened Gamma-Nought backscatter coefficient (γ_T^0), in complex number format, is provided for each polarization (e.g., HH, HV, VV, VH).

File format specifications/contents provided in metadata:

- Measurement Type (Gamma-Nought)
- Backscatter Expression Convention (linear amplitude, linear power*)
- Polarization (HH, HV, VV, VH)
- Data Format (GeoTIFF, HDF5, NetCDF, …)
- Data Type (Int, Float, …)
- Bits per Sample
- Byte Order

Notes:

1. Transformation to the logarithm decibel scale is not required or desired as this step can be completed by the user if necessary.

Geometric Corrections

The geometric corrections are steps that are taken to place the measurement accurately on the surface of the Earth (that is, to geolocate the measurement) allowing measurements taken through time to be compared. This section specifies any geometric correction requirements that must be met in order for the data to be analysis ready.

Digital Elevation Model (`geometric-corrections-corrections-dem`)

Goal requirements:

- A DEM with comparable or better resolution to the resolution of the output CEOS-ARD product shall be used if available. Else, the upsampled DEM is identified.
- Resampling method used for preparation of the DEM.
- Method used for resampling the EGM.

Threshold requirements:

Usage: For products including land areas.

- During ortho-rectification, the data provider shall use the same DEM that was used for the radiometric terrain flattening to ensure consistency of the data stack.
- Provide reference to Digital Elevation Model used for geometric terrain correction.
- Provide reference to Earth Gravitational Model (EGM) used for geometric correction.

References

International Organization for Standardization. 2009. “Geographic information — Metadata — Part 2: Extensions for imagery and gridded data.” Standard. Geneva, CH: International Organization for Standardization.

Lee, Jong-Sen, Jen-Hung Wen, T. L. Ainsworth, Kun-Shan Chen, and A. J. Chen. 2009. “Improved Sigma Filter for Speckle Filtering of SAR Imagery.” *IEEE Transactions on Geoscience and Remote Sensing* 47 (1): 202–13. https://doi.org/10.1109/TGRS.2008.2002881.

Shiroma, Gustavo H. X., Marco Lavalle, and Sean M. Buckley. 2022. “An Area-Based Projection Algorithm for SAR Radiometric Terrain Correction and Geocoding.” *IEEE Transactions on Geoscience and Remote Sensing* 60: 1–23. https://doi.org/10.1109/TGRS.2022.3147472.

Small, David. 2011. “Flattening Gamma: Radiometric Terrain Correction for SAR Imagery.” *IEEE Transactions on Geoscience and Remote Sensing* 49 (8): 3081–93. https://doi.org/10.1109/TGRS.2011.2120616.

Zebker, Howard. 2017. “User-Friendly InSAR Data Products: Fast and Simple Timeseries Processing.” *IEEE Geoscience and Remote Sensing Letters* 14 (October): 1–5. https://doi.org/10.1109/LGRS.2017.2753580.

Zebker, Howard A., Scott Hensley, Piyush Shanker, and Cody Wortham. 2010. “Geodetically Accurate InSAR Data Processor.” *IEEE Transactions on Geoscience and Remote Sensing* 48 (12): 4309–21. https://doi.org/10.1109/TGRS.2010.2051333.

Zheng, Yujie, and Howard Zebker. 2017. “Phase Correction of Single-Look Complex Radar Images for User-Friendly Efficient Interferogram Formation.” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* PP (May): 1–8. https://doi.org/10.1109/JSTARS.2017.2697861.

Annexes

General Processing Roadmap

The radiometric interoperability of CEOS-ARD SAR products is ensured by a common processing chain during production. The recommended processing roadmap involves the following steps:

- Apply the best possible orbit parameters to give the most accurate product possible. These will have been projected to an ellipsoidal model such as WGS84. To achieve the level of geometric accuracy required for the DEM-based correction, precise orbit determination will be required.
- Apply instrument calibration to produce Beta-Nought values with high fidelity.
- Convert Single-Look-Complex (SLC) radiometric channel(s) to intensity NRB, ORB and POL and in addition for POL, the cross-product element(s) of the covariance as shown in Section “**¿sec:annex-sar-pol-covmat?**”.
- Perform radiometric terrain correction (gamma backscatter convention terrain-flattening) on the covariance matrix by applying the local surface normalisation factor to each backscatter measurement element (Small 2011; Shiroma, Lavalle, and Buckley 2022).
- Perform polarimetric speckle filtering (optional for NRB and ORB), before geocoding, to optimally preserve the polarimetric information. Most popular polarimetric decomposition methodologies are incoherent in nature, which requires averaging the covariance matrix for stationarity. Depending on the application, a polarimetric filter that preserves local point targets and locally average extended targets may be used, e.g., Sigma Lee filter with 7x7 window and 3-point target (Lee et al. 2009). Multi-looking could be performed to meet optimal output sample spacing before the geometric correction step. No speckle filtering or multi-looking is performed for GSLC products.
- For GSLC products, the topographic phase is estimated relative to a reference orbit and removed from the SLC data (H. A. Zebker et al. 2010; H. Zebker 2017) (see Section “Topographic phase removal”)
- Geometric terrain correction (relative to geoid for ORB) is applied to the normalized backscatter measurement data. For POL, the resampling methodology should be nearest-neighbour, bilinear or average in order to preserve integrity of the covariance matrix as other resampling functions can introduce artefacts due to the mix of intensity and complex number elements in the matrix. Geocoding to a common grid structure with specified pixel spacings for true data cube format.
- Generate CEOS format metadata to accompany product layers.
- Optionally, a SpatioTemporal Asset Catalog (STAC) file is added to the product.

Table 1 lists possible sequential steps and existing software tools (e.g., Gamma software (GAMMA, 2018)) and scripting tasks that can be used to form the CEOS-ARD SAR processing roadmap.

Table 1: SAR ARD processing roadmap and software options. RADARSAT-2 Example

Step	**Implementation option**
1. Orbital data refinement	Check xml date and delivered format. RADARSAT-2, pre EDOT (July 2015) replace. Post July 2015, check if ‘DEF’, otherwise replace. (Gamma - RSAT2_vec)
2. Apply radiometric scaling Look-Up Table (LUT) to Beta-Nought	Specification of LUT on ingest. (Gamma - par_RSAT2_SLC/SG)
3. Generate covariance matrix elements	Gamma – COV_MATRIX
4. Radiometric terrain normalisation	Gamma - geo_radcal2
5. Speckle filtering (Boxcar or Sigma Lee)	Custom scripting
6. Geometric terrain correction/Geocoding	Gamma – gc_map and geocode_back
7. Create metadata	Custom scripting

Topographic phase removal

InSAR analysis capabilities from CEOS-ARD SAR products are enabled with GSLC products, which is also the case when the Flattened Phase per-pixel data (Section “**¿sec:measurements-measurements-flattened-phase?**”) are included in the NRB or POL products. This is made possible since the simulated topographic phase relative to a given reference orbit has been subtracted.

From classical approach with SLC data, interferometric phase $\Delta\varphi_{1-2}$ between two SAR acquisitions is composed of a topographic phase $\Delta\varphi_{\mathrm{Topo\_1-2}}$, a surface displacement phase $\Delta\varphi_{\mathrm{Disp\_1-2}}$ and other noise terms $\Delta\varphi_{\mathrm{Noise\_1-2}}$ (Eq. 1). The topographic phase consists to the difference in geometrical path length from each of the two antenna positions to the point on the SAR image ($\varphi_{\mathrm{DEM\_SLC}}$) and is a function of their orbital baseline distance (Eq. 2). The surface displacement phase is related to the displacement of the surface that occurred in between the two acquisitions. The noise term is the function of the radar signal interaction with the atmosphere and the ionosphere during each acquisition and function of the system noise.

$$\Delta\varphi_{1-2} = \Delta\varphi_{\mathrm{Topo\_1-2}} + \Delta\varphi_{\mathrm{Disp\_1-2}} + \Delta\varphi_{\mathrm{Noise\_1-2}} \qquad (1)$$

Where

$$\Delta\varphi_{\mathrm{Topo\_1-2}} = \varphi_{\mathrm{DEM\_SLC\_1}} = \varphi_{\mathrm{DEM\_SLC\_2}} \qquad (2)$$

Since CEOS-ARD products are already geocoded, it is important to remove the wrapped simulated topographic phase $\varphi_{\mathrm{SimDEM\_SLC}}$ from the data in slant range (Eq. 3) during their production, before the geocoding step. The key here is to simulate the topographic phase relatively to a constant reference orbit, as done in a regular InSAR processing. There are two different ways to simulate the topographic phase:

1. The use of a virtual circular orbit above a nonrotating planet (H. A. Zebker et al. 2010)
2. The use of a specific orbit cycle or a simulated orbit of the SAR mission

In both cases, the InSAR topographic phase $\Delta\varphi_{\mathrm{Topo\_OrbRef-2}}$ is simulated against the position of a virtual sensor $\Delta\varphi_{\mathrm{Topo\_OrbRef}}$ lying on a reference orbit, instead of being simulated relatively to an existing reference SAR acquisition ($\varphi_{\mathrm{DEM\_SLC\_1}}$). The use of a virtual circular orbit is a more robust approach since the reference orbit is defined at a fixed height above scene nadir and assuming the reference orbital height constant for all CEOS-ARD products. While with the second approach, the CEOS-ARD data producer must select a specific archived orbit cycle of the SAR mission or define a simulated one, from which the relative orbit, matching the one of the SAR acquisitions to be processed (to be converted to CEOS-ARD), is defined as the reference orbit. With this second approach, it is important to always use the same orbit cycle (or simulated orbit) for all the CEOS-ARD produced for a mission, in order to preserve the relevant compensated phase in between them. Providing absolute reference orbit number information in the metadata (item 1.7.15) allows users to validate the InSAR feasibility in between CEOS-ARD products.

$$\varphi_{\mathrm{Flattended\_SLC\_2}} = \varphi_{\mathrm{SLC\_2}} - \Delta\varphi_{\mathrm{Topo\_OrbRef-2}} \qquad (3)$$

This procedure is equivalent to bring the position of the sensor platform of all the SAR acquisitions at the same orbital position (i.e., zeros baseline distance in between), which results in a Flattened phase $\varphi_{\mathrm{Flattended\_SLC}}$, independent of the local topography.

The phase subtraction could be performed by using a motion compensation approach (H. A. Zebker et al. 2010) or directly on the SLC data. Then the geometrical correction is performed on the Flattened SLC, which results in a GSLC product.

GSLC can also be saved as a NRB product by including the Flattened Phase per-pixel data (Section “**¿sec:measurements-measurements-flattened-phase?**”) as follows:

$$\mathrm{NRB:} \quad \gamma_T^0 = |GSLC|^2$$

$$\text{Flattended Phase:} \quad \varphi_{\text{Flattended}} = \arg(GSLC)$$

For POL product, the Flattened phase needs also to be subtracted from the complex number phase of the off-diagonal elements of the covariance matrix.

Demonstration:

From CEOS-ARD flattened SAR products, InSAR processing can be easily performed without dealing with topographic features and orbital sensor position, as for example with two GSLC products

$$\varphi_{\text{Flattened\_GSLC\_1}} = \varphi_{\text{SLC\_1}} - \Delta\varphi_{\text{Topo\_OrbRef}-1} = \varphi_{\text{SLC\_1}} - \varphi_{\text{DEM\_OrbRef}} - \varphi_{\text{DEM\_SLC\_1}} \quad (4)$$

$$\varphi_{\text{Flattened\_GSLC\_2}} = \varphi_{\text{SLC\_2}} - \Delta\varphi_{\text{Topo\_OrbRef}-2} = \varphi_{\text{SLC\_2}} - \varphi_{\text{DEM\_OrbRef}} - \varphi_{\text{DEM\_SLC\_2}} \quad (5)$$

The differential phase is

$$\Delta\varphi_{\text{CARD\_1}-\text{CARD\_2}} = \varphi_{\text{Flattened\_GSLC\_1}} - \varphi_{\text{Flattened\_GSLC\_2}} \quad (6)$$

Which can be expanded using (Eq. 3)

$$\Delta\varphi_{\text{CARD\_1}-\text{CARD\_2}} = (\varphi_{\text{SLC\_1}} - \varphi_{\text{DEM\_OrbRef}} - \varphi_{\text{DEM\_SLC\_1}}) - (\varphi_{\text{SLC\_2}} - \varphi_{\text{DEM\_OrbRef}} - \varphi_{\text{DEM\_SLC\_2}}) \quad (7)$$

$$\Delta\varphi_{\text{CARD\_1}-\text{CARD\_2}} = (\varphi_{\text{SLC\_1}} - \varphi_{\text{SLC\_2}}) - (\varphi_{\text{DEM\_SLC\_1}}) - \varphi_{\text{DEM\_SLC\_2}}) \quad (8)$$

$$\Delta\varphi_{\text{CARD\_1}-\text{CARD\_2}} = \Delta\varphi_{\text{SLC\_1}-\text{SLC\_2}} - \Delta\varphi_{\text{Topo\_1}-2} \quad (9)$$

Where $\Delta\varphi_{\text{SLC\_1}-\text{SLC\_2}}$ can be express as Eq. 1, which gives

$$\Delta\varphi_{\text{CARD\_1}-\text{CARD\_2}} = (\Delta\varphi_{\text{Topo\_1}-2} + \Delta\varphi_{\text{Disp\_1}-2} + \Delta\varphi_{\text{Noise\_1}-2}) - \Delta\varphi_{\text{Topo\_1}-2} \quad (10)$$

Consequently, the differential phase of two CEOS-ARD products doesn’t contain a topographic phase and is already unwrapped (at least over stable areas). It is only function of the surface displacement and of the noise term. Depending on the reference DEM and the satellite orbital state vector accuracies, some residual topographic phase could be present. Atmospheric (item 2.15) and ionospheric (item 2.16) phase corrections could be performed during the production of CEOS-ARD products, which reduces the differential phase noise in an InSAR analysis.

$$\Delta\varphi_{\text{CARD\_1}-\text{CARD\_2}} = \Delta\varphi_{\text{Disp\_1}-2} + \Delta\varphi_{\text{Noise\_1}-2}) \quad (11)$$

Geocoded Single-Look Complex example

In contrast to basic NRB and **POL products**, CEOS-ARD Geocoded SLC GSLC products are kept close to the native resolution in complex data format for which local topographic InSAR phases, relative to a reference orbit (H. A. Zebker et al. 2010; H. Zebker 2017), have been removed. Having a volume of GSLC products acquired over repeat cycles, already radiometric and phase terrain corrected and geocoded (Figures 1, 2), allows user-friendly production of a first iteration of the InSAR coherence (Eq. 12, Figure 3) and differential phases (Eq. 13, Figure 4) in between GSLC pairs, simply by applying local averaging window over the product of a GSLC product (GSLC1) with the complex conjugate of a second GSLC (GSLC2) divided by their local averaged intensities. These intermediate files could be used for coherent change detection analysis and surface displacement monitoring.

$$\text{Complex coherence:} \quad \rho = \frac{\sum[GSLC_1 * conj(GSLC_2)]}{\sqrt{\sum|GSLC_1|^2 * \sum|GSLC_2|^2}} \quad (12)$$

The InSAR differential phase (Eq. 13) is the argument of the complex coherence estimated with Eq. 12.

$$\text{InSAR differential phase:} \quad \varphi = \arg(\rho) \quad (13)$$

Some advanced NRB or POL products could include per-pixel “Flattened Phase” data (Section “**¿sec:measurements-measurements-flattened-phase?**”). This “Flattened Phase” enables the possibility to perform InSAR analysis as with two GSLC products. As for example, from two different NRB products (NRB1) and (NRB2), acquired over repeat cycles (i.e., on the same relative orbit), containing γ_T^0 and their corresponding “Flattened Phase” (FPh1) and (FPh2) per-pixel data, the complex InSAR coherence (Eq. 14) can be estimated in the similar manner as Eq. 12 for GSLC products.

$$\text{Complex coherence:} \quad \rho_{NRB} = \frac{\sum[(\sqrt{NRB_1} \cdot e^{i \cdot FPh1}) \cdot conj(\sqrt{NRB_2} \cdot e^{i \cdot FPh2})]}{\sqrt{\sum NRB_1 * \sum NRB_2}} \qquad (14)$$

The following figures show Sentinel-1 GSLC product examples over Death Valley National Park, California, US:

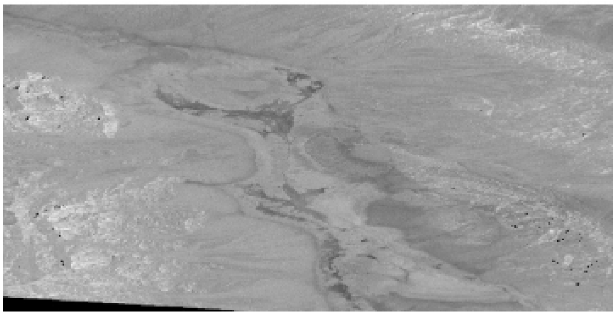

Figure 1: GSLC1: Intensity data of the first GSLC product (2017-05-27)

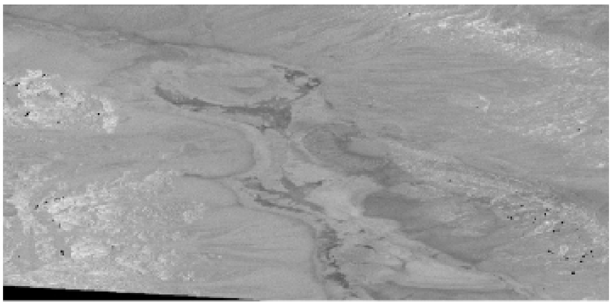

Figure 2: GSLC2: Intensity data of the second GSLC product (2017-06-08)

Figure 3: InSAR coherence map generated directly from Figure 1 and Figure 2

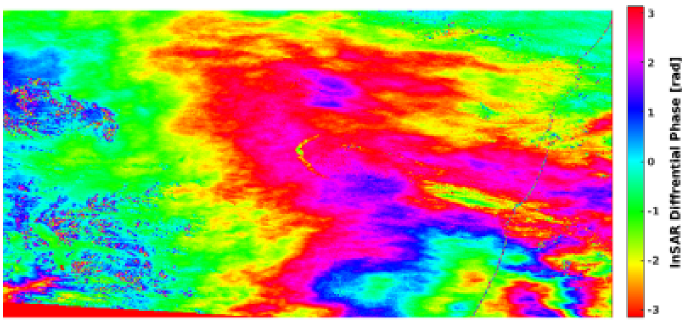

Figure 4: InSAR differential phase map generated directly from Figure 1 and Figure 2

Some advanced GSLC product can be provided with “Radar Unit Look Vector Grid Image” per-pixel metadata (Figures 5-7) which gives the accurate 3-D components radar unit look vector used as for example in decomposing the vertical and horizontal component of an InSAR surface displacement estimate.

The following figures show 3-D components radar unit look vector of the GSLC product:

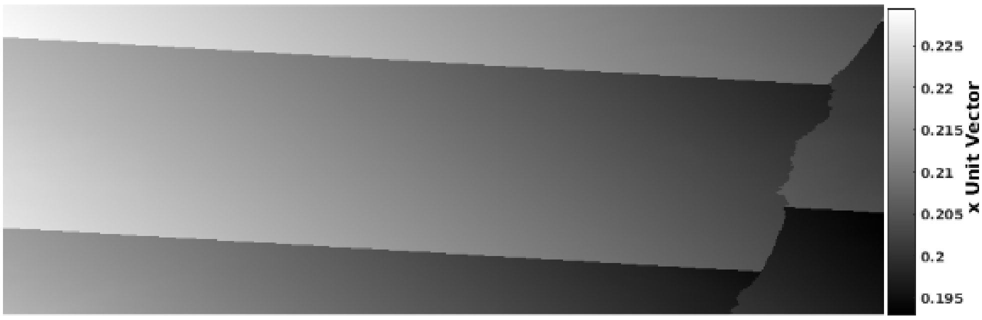

Figure 5: x unit component

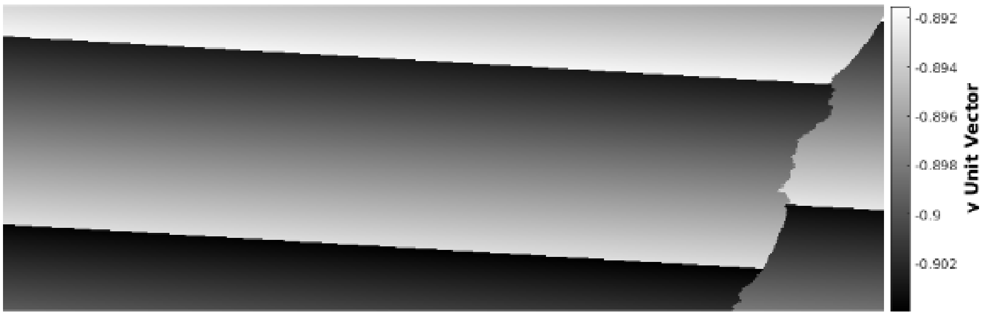

Figure 6: y unit component

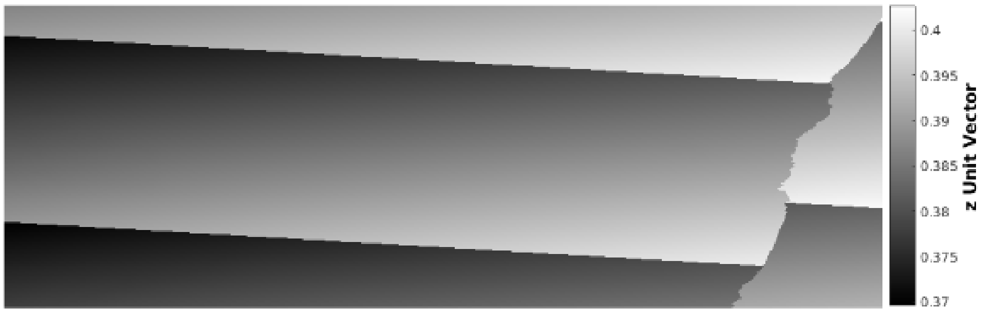

Figure 7: z unit component